yet there may be no radiological evidence of the site and size of the affected area. Even if a shadow is seen, it is usually ill-defined, and in the single posterior view, which is usually all that is available, there is no evidence of a pyramidal shape. If it is as small as 1 cm. it may be more or less circular, but when larger its ill-defined margins are often partly masked by a superadded pleural effusion.

When studying a skiagram of the lungs in a patient with cardiac disease, it must not be forgotten that other pathological conditions may co-

exist. For instance, a bronchial neoplasm may arise in a patient with long-standing, but well-compensated, mitral stenosis; while ordinary inflammatory conditions may occur in the lungs independently of the cardiac lesion. A coal miner with pneumonokoniosis may develop mitral stenosis, in which case it may be difficult to differentiate the shadows of the pneumonokoniosis from those of a possible haemosiderosis. It is therefore essential to consider the X-ray appearances from a broad angle of general medicine.

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ANGIOCARDIOGRAPHY

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Angiocardiography is now an established diagnostic procedure in the fields of thoracic and cardiac surgery. By intravenous injection of an opaque substance combined with rapid serial radiography it is possible to study the heart chambers and great vessels during life. The method was conceived more than 20 years ago, though its application in clinical medicine is recent. Improvements in radiological technique have encouraged wider use of the procedure but the interest in the diagnosis of congenital heart disease and the advances in its treatment, are mainly responsible for modern development of this method of investigation.

History

In 1929 Forssman first injected an opaque substance into the living human heart. Like later workers in this field, notably Ameuille (1936), Forssman used sodium iodide for the intravenous injection. In the quantity and concentration employed this substance gave good angiograms of the pulmonary arterial tree, but it was not sufficiently opaque to outline the heart chambers or the aorta. For this reason little progress was made in this method of investigation until Castellanos

(1938) and his co-workers in Cuba introduced the organic iodides as the contrast medium. With 35 per cent. neiopax these workers were able to show the right heart chambers and the aorta and its larger branches in children with cyanotic congenital heart disease. But, because of dilution in the pulmonary circulation, satisfactory angiocardiograms of the left heart in acyanotic conditions could not be obtained.

In 1938 Robb and Steinberg prepared and used a 70 per cent. aqueous solution of the diethanolamine salt of 3, 5-diiodo-4-pyridone-N-acetic acid for the intravenous injection. With this substance they were able to outline, first, the right heart chambers and pulmonary arteries and later the left heart and aorta. The introduction of multiple cassette-changing devices has enhanced the value of angiocardiography, but in other respects the procedure described by Robb and Steinberg is more satisfactory than any other and is in general use today.

Contrast Media

Diodone or diodrast, the material originally prepared by Robb and Steinberg, is still the most widely employed contrast medium in angio-

cardiography. The 75 per cent. solution of neoipax is used, but is less satisfactory because of its tendency to give rise to pain in the arm and shoulder during injection.

Diodone is freely miscible with blood, relatively inert and excreted rapidly, unchanged, by the kidneys. It produces transitory peripheral vasodilatation and slight fall in blood pressure. On reaching the systemic circulation it invariably gives rise to an unpleasant sensation of intense heat, often accompanied by a throbbing headache and occasionally by nausea and vomiting. Localized venous thrombosis at the site of injection is common and infrequently erythematous or urticarial eruptions occur. The toxic dose for man is not known, but 1.5 gm./kilo is thought to be entirely safe (Robb and Steinberg, 1939). On several occasions we have employed larger quantities and there have been no unpleasant sequelae.

Sensitivity to diodone is occasionally encountered and intravenous, intradermal and intra-ocular tests are employed to exclude sensitive subjects. Our practice is to inject $\frac{1}{2}$ ml. diodone diluted in 20 ml. saline intravenously. On three occasions this has been followed by a vasovagal attack and the investigation was abandoned. Sensitivity tests are not, however, infallible. Two patients who showed no reaction with the intravenous test experienced transitory intense dyspnoea when the diodone reached the pulmonary circulation.

Although Robb (1947) has reported no serious sequelae in more than 1,500 patients, deaths have followed angiocardiology in some instances (Taussig and Bing, 1949). Recently Dotter and Jackson (1949) have reported 26 fatalities in a total of 6,824 patients submitted to this procedure. The high incidence of cyanotic congenital heart disease among the patients investigated probably accounts for the considerable mortality rate. There is little doubt, however, that in any seriously ill subject angiocardiology involves some risk and it is our practice to defer it in such patients, unless it is expected to influence the immediate treatment.

Premedication and Anaesthesia

The immediate unpleasant effects of diodone can be mitigated to some extent by sedation; phenobarbitone or nembutal and nepenthe are satisfactory in adults and in most acyanotic conditions in children. In children with cyanotic congenital heart disease, on the other hand, the unpleasant sensation of heat and the intense headache occur early and are often very severe because the diodone is shunted directly into the systemic circulation. Moreover, these children are often

seriously ill and any manipulation or fright may induce a fatal cyanotic attack. In these circumstances, therefore, angiocardiology, if deemed essential, is best performed under general anaesthesia.

Technique of Injection

This has been fully described by Robb and Steinberg (1939) and only some details of the procedure require special emphasis.

The object of the injection is to produce an opaque intravascular bolus which will in turn outline each heart chamber and the great vessels. This can only be accomplished if a sufficient quantity of diodone is injected in a short time. Dilution of the contrast medium with venous blood inevitably occurs, even with rapid injection, and may prevent clear definition of the cardiac chambers if only a small quantity is used. Large quantities, injected over a period of three or four seconds, are equally unsatisfactory, since the angiocardigrams produced in this way consist of a mass of confusing shadows where right and left heart chambers and pulmonary and systemic vessels are superimposed.

The rate of injection should be at least 30 ml. per second and this speed can only be attained if the internal diameter of the cannula and the nozzle of the syringe are at least 2 mm. ($\equiv$ 14 B.S.W.G.). Further, some form of locking device should be incorporated in the nozzle of the syringe to prevent leakage during the injection. This is effected in the special Robb cannula by the Luer-Lok, and in this country syringes and cannulae with bayonet fixings can be obtained.

The quantity of diodone injected depends on the size of the patient and the size of the heart. In children 20 ml. is often sufficient. In adults with large hearts and in obese subjects amounts up to 70 ml. may be required. Our experience suggests, however, that there is nothing to be gained by increasing the quantity if the duration of the injection exceeds two seconds.

The right median basilic vein is selected for the injection if the superior vena cava is right-sided. In children the vein must be exposed and the cannula tied in, but in adults it is better to thrust the trocar and cannula directly into the vein.

The injection may be made with the patient supine or erect. The former position is essential in anaesthetized or heavily sedated subjects, but whenever possible the upright position is to be preferred. Not only does this allow of less distortion of the heart shadow, but in the upright position kinking of the subclavian vein at the thoracic inlet, which may interfere with rapid injection, is more easily avoided.

FIG. 1.—Normal heart, child aged 4½ years, antero-posterior position. ½-second film showing superior vena cava, right auricle, right auricular appendage and pulmonary trunk.

FIG. 2.—Normal heart, child aged 4½ years, antero-posterior position. 1½-second film showing right auricle and auricular appendage, right ventricle, pulmonary trunk, and right and left pulmonary arteries.

ABBREVIATIONS IN DIAGRAMS

SVC	Superior vena cava.
IVC	Inferior vena cava.
RA	Right auricle.
R. A. App.	Right auricular appendage.
RV	Right ventricle.
MPA	Main pulmonary artery.
RPA	Right pulmonary artery.
LPA	Left pulmonary artery.
LA	Left auricle.
L. A. App.	Left auricular appendage.
LV	Left ventricle.
Aa	Aorta.
Cor. Sinus	Coronary Sinus.

FIG. 3.—Normal heart, child aged $4\frac{1}{2}$ years, antero-posterior position. $3\frac{1}{2}$ -second film showing pulmonary veins, left auricle, left ventricle and aorta and its branches.

FIG. 4.—Normal heart, child aged $4\frac{1}{2}$ years, antero-posterior position. $4\frac{1}{2}$ -second film showing left auricle and auricular appendage, left ventricle and aorta.

FIG. 5.—Normal heart, woman aged 38, left anterior oblique position. 1-second film showing superior vena cava, right auricle, auricular appendage and coronary sinus, right ventricle and pulmonary trunk.

FIG. 6.—Normal heart, woman aged 38, left anterior oblique position. 3-second film showing right ventricle, pulmonary trunk and its right and left branches.

FIG. 7.—Normal heart, woman aged 38, left anterior oblique position. 7-second film showing pulmonary veins, left auricle and ventricle and aorta.

FIG. 8.—Normal heart, girl aged 18, right anterior oblique position. 1-second film showing superior vena cava, right auricle and ventricle and pulmonary trunk.

FIG. 9.—Normal heart, girl aged 18, right anterior oblique position. 7-second film showing pulmonary veins, left auricle and the aorta.

FIG. 10.—Mitral stenosis, woman aged 34, antero-posterior position. 2-second film showing superior vena cava, right auricle and ventricle, pulmonary trunk and right and left pulmonary arteries.

FIG. 11.—Mitral stenosis, woman aged 34, anteroposterior position. 10-second film showing pulmonary veins, left auricle and aorta.

FIG. 12.—Mitral stenosis, child aged 8, left lateral position. 2-second film showing right auricle and ventricle and pulmonary trunk and right and left pulmonary arteries.

FIG. 13.—Mitral stenosis, child aged 8, left lateral position. 7-second film showing pulmonary veins, left auricle and ventricle and aorta.

FIG. 14.—Syphilitic aortitis, man aged 56, left anterior oblique position. 9-second film showing aortic arch.

FIG. 15.—Hypertensive heart disease, woman aged 54, left anterior oblique position. 7-second film showing left auricle and aorta.

FIG. 16.—Aneurysm of the innominate artery, woman aged 50, antero-posterior position. Teleradiogram.

FIG. 17.—Aneurysm of the innominate artery, woman aged 50, antero-posterior position, 9-second film showing aneurysm of the innominate artery.

FIG. 18.—Coarctation of the aorta, girl aged 20, left lateral position. 9-second film showing coarctation of the aorta proximal to the origin of the dilated left subclavian artery.

FIG. 19.—Patent ductus arteriosus, girl aged 17, left lateral position. Film showing bulge on the aorta, marked by arrow in the diagram.

FIG. 2c.—Eisenmenger complex, child aged 9, antero-posterior position. 2-second film showing simultaneous filling of aorta and pulmonary trunk and dense pulmonary vascular markings.

FIG. 21.—Fallot's Tetralogy, child aged 10, antero-posterior position. 2-second film showing simultaneous filling of aorta and pulmonary trunk and translucent lung fields. The dotted line in the diagram indicates the position of a catheter in the right pulmonary artery (from composite tracings).

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The Circulation Times

In normal children diodone may reach the carotid arteries within four seconds of its injection into an antecubital vein and the difficulty of rapid film changing constitutes the chief problem of angiocardiology. In adults, on the other hand, it may be 20 or more seconds before the aorta is outlined and the problem here is to determine the optimum times for the exposures. The arm-lung and arm-tongue circulation times are some indication, provided the material employed is injected through the large-bore syringe and cannula. We have found a modified arm-tongue time, determined by injecting 5 gm. of saccharin diluted in 20 ml. of saline, to be the most reliable guide to the time when diodone first appears in the carotid arteries. Films taken one second before this time and for 1-2 seconds after it usually show the left heart chambers and the aorta. But no way of estimating the circulation time is infallible, excepting only the injection of a full dose of diodone itself, and in a few instances we have been forced to employ this procedure.

CLINICAL APPLICATIONS

The Normal Angiocardiogram

Angiocardiographic studies in normal subjects have been made in several centres (Robb and Steinberg, 1940; Taylor and McGovern, 1943; Sussman and Grishman, 1947; Chavéz *et al.*, 1947). These studies have confirmed in many respects and in a few have corrected the accepted interpretation, based on fluoroscopic study, of the cardiac contour. Further, by indicating the extent of the chambers lying within that contour, they have afforded a clearer conception of living cardiac anatomy. We have made angiocardiograms in a small number of normal subjects in different age groups in the three standard positions used at fluoroscopy. Not only have they shown something of the scope and limitations of the technique, but they provide a useful standard by which to judge the abnormal.

Antero-Posterior Position

In the antero-posterior position the cardiac chambers and both right and left auricular appendages are clearly defined and the anatomy of the systemic arteries arising from the arch of the aorta can generally be recognized. On the other hand, it is often difficult to determine with certainty the exact position of the aortic and pulmonary valves because the former are superimposed on the shadow of the left auricle and the latter on that of the backwardly directed pulmonary trunk.

Figures 1-4 are the antero-posterior angio-

cardiograms of a normal child aged 4½ years. The films are taken at one-second intervals, starting half a second after the beginning of the injection, and the first, second, fourth and fifth films of the series are shown. The presence of diodone in the pulmonary artery and aorta, half a second and three and a half seconds respectively, after the beginning of the injection, is objective evidence of the rapid circulation times in these small subjects.

Left Anterior Oblique Position

The main pulmonary artery and its left branch, the arch of the aorta and the situation of the aortic valves are seen best in this position and the ventricular septum and the left heart chambers are usually, but not always, clearly defined. On the other hand, the right auricle and ventricle are superimposed and the pulmonary valves are rarely seen because they overlie the root of the superior vena cava and the right auricular appendage. The right pulmonary artery is seen end on, and the dense rounded shadow indicating its origin is a useful landmark when the presence of the pulmonary arteries is in doubt.

Figures 5-7 illustrate the normal appearances in the left anterior oblique position. In addition, they show two rather unusual features: in the one-second film a short segment of the coronary sinus is seen as a wide channel curving upwards and backwards from the posterior margin of the right auricle, and in the seven-second film a small bulge distorts the usually smooth contour of the aortic arch at its junction with the descending aorta.

Right Anterior Oblique Position

The situation of the pulmonary valves is seen better in this position than in any other. The heart chambers are often well seen, but the root of the aorta is rarely defined clearly because it is superimposed on the shadows of the left auricle and the pulmonary veins.

Figures 8 and 9 illustrate the normal appearances in an 18-year-old girl in the right oblique position.

Rheumatic Heart Disease

Angiocardiographic studies in rheumatic heart disease have been made by Grishman and Sussman (1944). These workers maintain that in mitral stenosis the pulmonary arc is formed in its upper part by the pulmonary artery either alone or with its left branch, and in its lower part by the left auricular appendage. In some of our patients, however, the appendage has appeared to be situated well within the cardiac silhouette and to take no part in the contour of the pulmonary arc. It is possible that in these instances the tip of the

appendage contained blood clot or faulty timing of the exposures may have prevented its complete definition.

Figures 10 and 11 are the angiocardiograms of a woman aged 34 with well-developed mitral stenosis. The pulmonary arc in this instance is formed entirely by the main pulmonary artery and its left branch and the left auricular appendage is some distance from the left border of the heart.

Grishman and Sussman have shown that in mitral stenosis the left auricle is enlarged in all directions; it invariably contributes to the upper right cardiac contour and its forward enlargement results in elongation and displacement of the out-flow tract of the right ventricle and the pulmonary artery.

The large left auricle is certainly the most striking feature of angiocardiograms in mitral stenosis. It is appreciated most readily in the left oblique or left lateral positions, where the forward and upward enlargement is seen to displace the right heart chambers and the pulmonary artery. It is probably this elevation of the pulmonary artery, so that it is directed upwards rather than backwards, that is primarily responsible for the prominent pulmonary arc so characteristic of mitral stenosis.

Figures 12 and 13, the angiocardiograms of an 8-year-old child with mitral stenosis, illustrate the effect of enlargement of the left auricle on the anatomy of the right heart and pulmonary artery.

Syphilitic Aortitis

Angiocardiography has become a useful procedure in suspected syphilitic aortitis. Figure 14, the angiocardiogram of a 56-year-old man, shows the local bulging and loss of parallelism of the aortic walls, characteristic of specific aortitis. These features are readily distinguished from the uncoiled aorta of hypertensive heart disease (Figure 15), where the walls of the aorta are smooth and the calibre decreases uniformly as the vessel is traced from its origin.

Aneurysm and Mediastinal Tumour

Robb and Steinberg (1940) were the first to demonstrate the value of contrast media in the differential diagnosis of aneurysm and mediastinal tumour, and more recently Sussman (1948) has published an excellent study of this subject. An aneurysm, unless completely thrombosed, becomes opaque at the same time as its vessel of origin. A tumour, on the other hand, though it may deform or displace the great vessels, does not become opaque. Figure 16 is the telerradiogram of a

woman aged 50 who complained of dysphagia. The shadow in the superior mediastinum suggests an intrathoracic goitre, but the angiocardiogram (Figure 17) shows that it is, in fact, a thick-walled aneurysm of the innominate artery.

CONGENITAL HEART DISEASE

I. Acyanotic Group

Coarctation of the Aorta

Within the last few years coarctation of the aorta has become amenable to surgery in some instances (Crafoord and Nylin, 1945). Diagnosis of this condition presents no difficulty and the indications for operation are based on clinical considerations, but the practicability of resection depends on the site and extent of the coarctation and this can only be determined by angiocardiography or thoracotomy. Several variations in the exact anatomy of the aortic arch may be encountered and these have been discussed by Salerni and Wiklund (1948). The commonest site of maximal stenosis is 2-3 cm. beyond the origin of the left subclavian artery, but in some instances it is immediately distal to the artery and rarely it may be proximal to the latter.

Figure 18 is the angiocardiogram of a patient aged 20 years in whom the degree of coarctation as judged by the clinical findings was severe. It is an example of the rare type of coarctation where the narrow segment is proximal to the left subclavian artery and the artery itself and the distal aorta are dilated.

Isolated Valvular Lesions

Stenosis of the pulmonary or aortic valves has been shown in only a few instances by angiocardiography (Grishman *et al.*, 1947). Associated anomalies, however, such as dilatation or hypoplasia of the great vessels are easily demonstrated.

II. Arterio-Venous Shunts ; Septal Defects and Patent Ductus Arteriosus

Angiocardiography may provide direct or indirect evidence of these anomalies. The direct evidence is early filling of the left auricle or ventricle from the right heart in atrial or ventricular septal defect respectively (Keele, 1948). The indirect evidence of such defects and of patency of the ductus arteriosus is the reappearance of diiodone in the right heart chambers after it has reached the left heart and aorta (Sussman and Grishman, 1947; Keele, 1948).

It is clear that the pressure differences which normally exist between the left and right sides of the heart should make direct visualization of these defects difficult. We have only seen this directed

evidence in complicated anomalies where the shunt is from right to left and we have never seen it in an isolated atrial or ventricular septal defect. Recirculation of diodone, the indirect evidence of intracardiac arterio-venous shunts, must, moreover, be diagnosed with caution. Where there is a large left to right shunt, with or without pulmonary incompetence, there is always much dilution of diodone in the right heart and pulmonary arteries and these structures remain outlined for many seconds after injection. Furthermore, in any condition, diodone held up at the thoracic inlet by faulty positioning of the arm may give rise to late ghost shadows of the right heart chambers. In a small group of 20 patients with intracardiac arterio-venous shunts or a patent ductus arteriosus we have not seen convincing evidence of recirculation.

In persistent patency of the ductus arteriosus direct evidence of the abnormal channel is rarely seen but an abnormality of the contour of the aorta is said to be very constant (Sussman and Grishman, 1947). This is a local bulge or a more extensive irregularity on the antero-inferior aspect of the arch at its junction with the descending aorta. We have not seen an instance of patency of the ductus arteriosus where the outline of this part of the aorta was normal, but we have seen local bulges in this situation in normal subjects (Figure 7). Further, it should be emphasized that, although the abnormality is easy to identify when the shunt is small, when it is large the aorta may be poorly defined owing to dilution of diodone in the lesser circulation and the irregularity of its contour may be obscured by dense pulmonary vascular shadows.

Figure 19 illustrates the abnormal contour of the aorta in a 17-year-old girl with a patent ductus arteriosus.

III. Morbus Coeruleus

The most valuable contribution angiocardiography has made to modern cardiology is probably in the field of cyanotic congenital heart disease. The advances in the surgery of this condition initiated by Blalock and Taussig (1945) in the United States and by Brock (1948) in this country call for accurate anatomical diagnosis.

The surgical procedures are designed to increase the blood supply to the lungs. The Blalock operation is only feasible if both right and left pulmonary arteries and a systemic vessel, suitable for anastomosis, are present. Valvulotomy demands a patent pulmonary trunk. In selecting cases suitable for operation, therefore, it is necessary, first, to exclude those cyanosed patients in whom the pulmonary blood flow is adequate or increased

and, secondly, to establish the presence of the pulmonary arteries.

Angiocardiograms in patients with increased pulmonary blood flow show dense pulmonary vascular markings often for six or eight seconds after the injection and there is no delay in filling the pulmonary arteries. By contrast, the translucency of the lungs in children with diminished pulmonary blood flow is striking; the pulmonary arteries are seen in only one, or at the most in two, films of the series, and there is always some delay in their filling. The recognition of this delay depends on a standard technique, and for this reason the translucent appearance of the lung fields is probably more reliable evidence of pulmonary stenosis. In our experience the exact site of the pulmonary stenosis can rarely be determined with certainty by angiocardiography.

The relative densities of the pulmonary and aortic shadows are a rough measure of the right to left shunt and the pulmonary blood flow. Slight aortic density suggests a small shunt, whereas a dense aortic shadow is evidence of a large shunt and considerable pulmonary stenosis.

The Eisenmenger complex is an example of cyanotic heart disease with increased pulmonary blood flow. Figure 20 is the two-second film of a 9-year-old child with an abnormality of this type. Both the pulmonary arteries and the aorta are filled with diodone and the solid density of the former, compared with the slighter aortic shadow, suggests that the right to left shunt is not large. In this and subsequent films the dense vascular shadows in the lung fields are evidence of increased pulmonary blood flow.

In cyanotic congenital heart disease with diminished pulmonary blood flow the circulation to the alveoli is effected by pulmonary arteries, or by bronchial arteries and other collaterals, or, in some instances, by both pulmonary and bronchial arteries. In the presence of pulmonary stenosis the pulmonary arteries fill from the right ventricle and they are always clearly seen in angiocardiograms, even if the stenosis be extreme. When, however, there is pulmonary atresia, the pulmonary arteries, if patent, fill from collateral vessels, and in these circumstances they may be difficult to define. The 'hilar comma' (Danelius, 1942) of the left or right pulmonary artery can often be recognized in teleradiograms of the chest and with experience it can be distinguished from the nodular hilar shadows characteristic of bronchial arteries. But it is often impossible to make this all-important distinction with certainty and it is pre-eminently for this reason that angiocardiography has become an essential pre-operative investigation in these patients. Campbell and Hills (1950) have recently made a comprehensive

study of this subject, based on a large number of cases, and they have emphasized the distinctive features of pulmonary and bronchial arteries.

The Tetralogy of Fallot is the commonest example of cyanotic congenital heart disease in which the blood supply to the lungs is inadequate.

Figure 21 is the two-second angiocardio-gram of a 10-year-old child. The aorta and pulmonary artery are equally dense and the lung fields in this and subsequent films are unusually translucent, suggesting considerable pulmonary stenosis. The approximate site of the stenosis, determined at right heart catheterization, is indicated in the diagram and the post-stenosis dilatation of the pulmonary artery is clearly seen in the angiocardio-gram. In the antero-posterior position the relation of both right and left subclavian arteries to the pulmonary arteries is displayed and for this reason it is the position of choice for angiocardio-graphy in uncomplicated Fallot's Tetralogy. When the existence of pulmonary arteries is in doubt additional films in the oblique position are essential.

Summary and Conclusion

Advances in the study of the living human heart have been furthered by angiocardio-graphy and progress in this technique will add much to the understanding of the subject. At present inter-

pretation is often difficult, partly because exposures are made too infrequently and partly because of changes in heart position and chamber size in systole and diastole. Improved radiological technique, particularly means of making the exposures at selected times in the cardiac cycle and simultaneous exposures in the antero-posterior and oblique positions, will ease the difficulties and afford a clearer picture of the anatomy and dynamics of the heart in health and disease.

In the fields of thoracic and cardiac surgery, wider use of angiocardio-graphy should decrease the need for exploratory thoracotomy.

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